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How Changes in Survivability and Lethality Affect Performance in a L400 Setting

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ABSTRACT

We investigate how changes in both survivability and lethality of vehicle options, in a Land 400 setting, affect mission performance. To do this, we construct a quadratic linear regression model with the survivability and lethality as two predictors and various measures of effectiveness as the result. This is done over two separate wargame cases with different vehicle options.

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Executive Summary

DSTO's Land Operations Division (LOD) has undertaken a series of close combat experiments, focused on combat teams at the platoon level under the Micro Combat Team (MCT) campaign. This work has so far focused predominantly on close combat in complex urban environments through two series of experiments, a light infantry series, and a mechanised series. This report is a side extension from the reports on the mechanised series.

Within the reports on the mechanised series, a key theme was the influence of how varying survivability and lethality affects the mission performance of the platoon. Within the reports on the mechanised series, various vehicle options were directly compared with both qualitative and quantitative evidence being obtained. Under the assumption that small changes in survivability or lethality would not change the scheme of manoeuvre, this report investigates how these changes affect mission performance.

To achieve this, two CAEn wargames are replicated with the changes in survivability and lethality applied. The two wargame cases include a medium and high survivability/lethality combination. Both cases are set in a high complexity urban setting against an insurgent enemy. A multiple linear regression model is fitted to the obtained data and results are taken from these models. The results are summarised in the following dot points:

- For the medium-weight vehicle case:
  - Increasing either survivability or lethality will initially improve mission performance almost equally.
  - There is increasing marginal utility for survivability. That is, even more improvements are obtained as survivability is increased more.
  - The improvements in lethality are linear.
- For the heavy-weight vehicle case:
  - Increasing survivability will improve mission performance only slightly and then start to reduce mission performance if it is improved too much.
  - Increasing lethality will improve mission performance greatly but this effect diminishes. That is, there is decreasing marginal utility in lethality.

The results from this analysis will inform key stakeholders (Land 400), provide robust wargame records for future capability analysis and increase DSTO's understanding of MCT operations with combat vehicles in complex urban terrain.

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Luke Finlay graduated from the University of South Australia in 2007 with a PhD in mathematics and a bachelor of information technology (Computing and Mathematics) with honours. Luke joined Land Operations Division in June 2007. He has worked mostly with the Micro Combat Team studies and the Army After Next studies.

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Glossary

MCT	Micro Combat Team
LOD	Land Operations Division
L400	Land 400
L125	Land 125
OFn	Objective Force n. $n \in \{1, 2, 3\}$
EXFOR	Experimental Force
OPFOR	Opposing Force
UGV	Unmanned Ground Vehicle
SoM	Scheme of Manoeuvre
IFV	Infantry Fighting Vehicle
CAEn	Close Action Environment
HE	High Explosive
HEAT	High Explosive Anti-Tank
RPG	Rocket Propelled Grenade
UGV	Unmanned Ground Vehicle
MoE	Measure of Effectiveness
HMMWV	High Mobility Multi-Purpose Wheeled Vehicle
ASLAV	Australian Light Armoured Vehicle

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1 Introduction

The Micro Combat Team (MCT) campaign has been established by Land Operations Division (LOD) to inform decisions for combat related projects within Army, including projects Land 400 (L400) and Land 125 (L125). Thus far, five experiments have been conducted supporting L400, culminating in six publications.

The last three publications, based on L400, Objective Force 1 (OF1) [Shine, Coutts & Dexter 2007], Objective Force 2 (OF2) [Finlay et al. 2008] and Objective Force 3 (OF3) [Shine et al. 2009] provide the immediate background to the research covered in this report. OF1 explored the impact of five combat vehicle and Unmanned Ground Vehicle (UGV) options, chosen from a matrix of three each of the respective systems. OF2 looked at the same options in a more complex environment. OF3 examined three vehicle options in both low and high complexity terrain and against both an insurgent and semi-symmetric Opposing Force (OPFOR).

One of the experimental questions investigated in OF3 was "How do different levels of lethality and survivability contribute to mission effectiveness in the different situations explored?" While the question was addressed within OF3, this report aims to extend the understanding of how small changes in lethality and survivability contribute to mission effectiveness, with a fixed Scheme of Manoeuvre (SoM), using a regression model.

2 Background

Within OF1 [Shine, Coutts & Dexter 2007] and OF2 [Finlay et al. 2008], a spread of three lethality and survivability options were compared along with the level of UGV augmentation. In OF3 [Shine et al. 2009], three sets of vehicle options were considered, as shown in Table 1. In this report, we only use the medium weight and heavy weight options from two wargames in OF3.

Table 1: *Vehicle group options in OF3*

Option	Infantry Fighting Vehicle	Direct Fire Support
Light	Joint Land Tactical Vehicle (JLTV) - The designated successor to the HMMWV, currently in the conceptual design stage of development.	Piranha V 35mm - The 35mm variant of the Piranha V vehicle, the latest in the family of vehicles that includes the ASLAV.
Medium	Piranha V 12.7mm - The personnel carrier version of the Piranha V.	CV90-35 - Swedish IFV, heavily armoured and equipped with a 35mm auto-cannon.
Heavy	CV90-35.	M1A1 Abrams Main Battle Tank.

In comparing the results from OF1 and OF2, the OF2 report found that "both environments tended to favour high lethality options with some level of UGV augmentation - with the exception that higher survivability may have compensated for reduced lethality in OF1." Here, "both environments" refers to high and medium complexity scenarios set in Fallujah and Binh Ba, respectively. This lead the next experiment in the series (OF3) to focus directly on both qualitative and quantitative analysis of the survivability and lethality of vehicle options. The qualitative analysis, based on a varying SoM between options, found that:

- Ideally, the Exercise Force (EXFOR) desired an option set that afforded significant amounts of survivability and lethality.
- Survivability was a key factor in the willingness of EXFOR to commit vehicles to key tasks such as dominating fire lanes and supporting the assault.
- Lethality was a key factor in the effectiveness of EXFOR vehicles when employed to perform key tasks.

When investigating survivability and lethality using quantitative analysis, wargames with varying weapon systems and complexity were compared. It was reported that survivability tends to improve as the option gets heavier but this rate of improvement diminishes. However, player perceptions were not in agreement with the diminishing component of the finding. This report investigates this diminishing aspect by using a linear regression model and observing how changes in lethality and survivability affect outcomes.

3 Defining Survivability and Lethality

We are interested in investigating how small changes in survivability and lethality affect mission performance. Under the assumption that any "small" change in survivability or lethality will not change EXFOR's SoM, we can use existing wargames with slightly modified vehicles. To achieve this, we used wargames from OF3 [Shine et al. 2009] with modified vehicle armour and weapons. We define how to change the survivability and lethality of EXFOR vehicles in the Close Action Environment (CAEn) wargame [Shine 2009] in the following subsections.

Both survivability (s) and lethality (l) are defined as being between 0 and 2 where the original *baseline* value is 1. That is, to replicate the original results from OF3, set both s and l to 1. The analysis presented here focuses on changes in survivability and lethality of EXFOR vehicles around the baseline case. Other EXFOR units remain unmodified as do all OPFOR units when s and l are changed.

3.1 Survivability

In the scenarios that we are considering, vehicles in CAEn can only be killed by OPFOR when high explosive anti-tank (HEAT) rounds, such as a Rocket Propelled Grenade (RPG), are used. When an OPFOR HEAT round is fired at an EXFOR vehicle, CAEn uses five factors in a lookup table to calculate the probability of kill p_k. The factors are range, elevation, angle, cover and whether or not the two respective units are moving. The multiple probabilities of kill in the lookup table are changed to influence the survivability of EXFOR vehicles.

Define the survivability variable (s) to be in the range $S = [0, 2]$. A linear scale is used such that $s = 0$ means that all p_k are increased by 100% and a survivability of $s = 2$ reduces all p_k by 100%. That is, multiply all p_k values by $(2 - s)$. The original p_k values have been calculated for each vehicle and HEAT round, as used in OF3 [Shine et al. 2009].

A survivability of $s = 0$ does not necessarily imply that all vehicles will be killed if a weapon is fired at them. For example, if the p_k of a tank (in a certain situation) was 0.3 and we let $s = 0.5$, the same p_k would be changed to 0.45. Likewise, by letting $s = 2$, all vehicles become invulnerable. UGVs are not affected by changes in the survivability variable.

To illustrate the overlap in vehicle survivability, Figure 1 shows the relative average probability of kill for three vehicles when attacked with an RPG-7. When $s = 2$, the probability of kill is 0 for all three vehicles. Clearly, the survivability of the vehicle is very dependent on which vehicle is chosen. For example, the M1A1 has a lower probability of kill when $s = 0$ in comparison to the CV90-35 with $s = 1.5$.

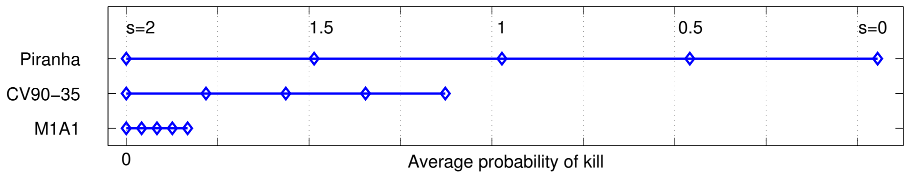

Figure 1: *Relative survivability of the three vehicles used in this report*

3.2 Lethality

Modelling changes in lethality are not as straightforward as changes in survivability. The overall lethality of a vehicle depends on the lethality of the individual weapon systems available to that particular vehicle. Therefore, when adjusting the lethality $l \in L = [0, 2]$ within an option, we adjust the lethality of all weapon systems for all vehicles. The lethality modification is broken up into three categories: accuracy, time to fire and probability of kill. The two classes of weapons in CAEn, relevant to this report, are bullet and high explosive (HE), which are modelled differently. Table 2 summarises how lethality is modified for both bullet and HE weapon types.

Table 2: *Types of data for bullet and HE weapon types*

	Bullet Weapons	**HE Weapons**	**Multiplier**
Aim Time	Time taken to aim the weapon		$(2 - l)$
Azimuth Error	Horizontal angle (rad)	Horizontal error (m)	$(2 - l)$
Elevation Error	Vertical angle (rad)		$(2 - l)$
Range Error		Range error (rad)	$(2 - l)$
Kill Probability		Set of p_k values	l

The bullet weapon type is used to model rifles, machine guns and tank rounds. Within CAEn, many aspects of the weapon system are modelled. However, regarding lethality, we are only interested in two aspects. The first sets the amount of time it takes for the unit to aim the weapon. Rather than defining a rate of fire of the weapon, we can change the aim time instead. The aim time values are multiplied by $(2-l)$.

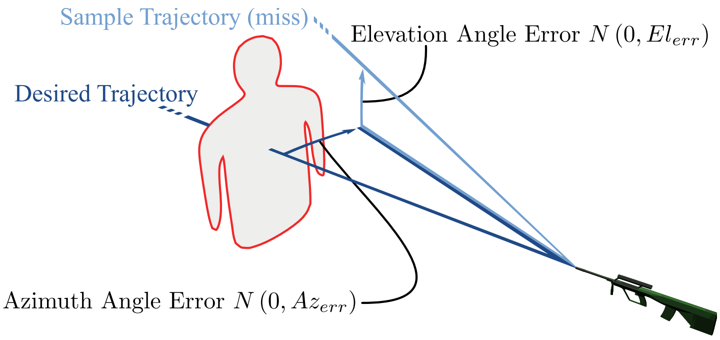

Figure 2: *Bullet trajectory "cone" model*

The second aspect of the bullet weapon type is the accuracy. Accuracy is defined by two angles, displayed in Figure 2. The azimuth error defines the amount of horizontal error while the elevation error defines the vertical error. Both errors are defined in terms of angle in radians, drawn from a normal distribution with mean $\mu = 0$ and the variance σ^2 defining the actual error. The set of possible trajectories can be thought of as a "cone". However, due to the nature of the normal distribution, the cone is not bounded and the errors could possibly (with an extremely low probability) fire in the opposite direction than was intended. In practice, the variances are very small since any error is propagated as the target is moved further away. In order to change the accuracy, the two angular errors are multiplied by $(2-l)$.

Similar to bullet weapons, HE weapons have an aim time which is modified in the same way. However, HE weapons do not use the cone model of accuracy. While there is still an Azimuth error, it is not based on an angle but based on a unit measure of distance. There is also an independent range error which is also based on a unit measure of distance. Like the bullet weapon model, these two errors are drawn from a normal distribution with mean $\mu = 0$ and a variance σ^2 set by the weapon type. The variances are multiplied by $(2-l)$. Figure 3 shows how these two error terms are combined to find the landing position of the HE round.

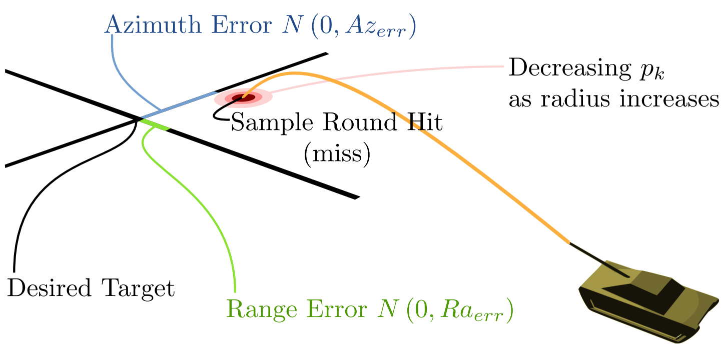

Figure 3: *High Explosive model - trajectory result is based on two normal distributions*

The other piece of information used to change the lethality of HE weapons is the probability of kill p_k. The probability of kill for a particular target unit depends on three factors. These factors are the distance from where the HE round landed, the posture of the unit and the type of terrain where the HE round landed. For our analysis, we multiply all probabilities over all three factors by l.

4 Defining Performance

As the survivability and lethality are changed, we are interested in variations in a set of measures of effectiveness (MoE). A common set of MoEs used in the MCT series of experiments are:

- **EXFOR Casualties.** This metric is defined as a primary factor for performance calculations and is represented as a set of human EXFOR casualty figures for each closed-loop simulation run of the CAEn wargames.
- **Civilian Casualties.** This metric, similar to EXFOR casualties, is a primary factor for performance calculations but represents civilian casualties.
- **OPFOR Casualties.** OPFOR casualties were considered a secondary factor for performance calculations and were represented as a set of human casualty figures for each closed loop simulation run of the CAEn wargames.
- **EXFOR Vehicle Casualties.** This metric is a direct indicator of the vulnerability of the vehicles in any particular option. Casualties of vehicles can either be partial damage or catastrophic kills.
- **Urban Damage.** A low level of damage to infrastructure was considered as important as minimising OPFOR and EXFOR Vehicle casualties. This metric is defined as a secondary factor for performance calculations.
- **Sensitive Urban Damage.** A low level of damage to sensitive buildings was considered as important as minimising EXFOR and civilian casualties. This metric is defined as a primary factor for performance calculations.

We consider the first four of these MoEs independently and Table 3 shows the MoEs with their relative weighting and variable names. The two Urban Damage MoEs are not used because they are not directly influenced by changes in survivability or lethality.

An overall mission performance metric is also considered using the weights defined in Table 3. Each of the MoEs are normalised by dividing by the total number of the respective quantity. For example, the number of EXFOR casualties is divided by 36. To construct the overall performance metric, these values are summed using the following performance formula for wargame i:

$$P_i = 2\left(1 - \frac{E_i}{36}\right) + \frac{O_i}{46} + 2\left(1 - \frac{C_i}{31}\right) + \left(1 - \frac{V_i}{10}\right). \tag{1}$$

Table 3: *Measures of effectiveness and weights*

Measure of Effectiveness	Variable	Weight	Max. Possible
EXFOR Casualties	E	2	36
OPFOR Casualties	O	1	46
Civilian Casualties	C	2	31
EXFOR Vehicle Casualties	V	1	10

Note that the range of equation (1) is $[0, 6]$ because all of the MoEs are normalised. Since we want to minimise all casualty types except OPFOR casualties, we take one minus the MoE in most cases. This results in a higher value of P_i meaning "better" mission performance. The four MoEs from Table 3 plus the performance metric are used to construct multiple linear regression models, totalling five separate models as shown in Section 6. For the use of the performance metric, it is assumed that the MoEs are independent.

5 Method of Analysis

The technique of multiple linear regression is often used to find correlations between a set of predictor variables and a result (see [Wetherill 1986, Hocking 1976]). The two predictor vectors were discussed in Section 3 and the multiple response vectors were discussed in Section 4. The general linear regression model that is used is of the form:

$$y_i = \beta_1 x_{i1} + \beta_2 x_{i2} + \cdots + \beta_j x_{ij} + \varepsilon_i, \qquad i = 1, \ldots, n, \tag{2}$$

where y_i is the response variable, x_i are the predictor variables, β is a p-dimensional parameter of the regression coefficients and ε_i are the residual errors. The response variable y_i we use is from Table 3 or Equation (1). We use the linear least squares method to find β with the equation

$$\beta = \underset{\beta}{\operatorname{argmin}} \sum_{i=1}^{n} \left(y_i - \sum_{j=1}^{p} \beta_j x_{ij} \right)^2 . \tag{3}$$

To analyse the wargame replication data, we consider a general two dimensional quadratic formula in survivability and lethality (with $p = 6$):

$$y_i = \beta_1 + \beta_2 s_i + \beta_3 l_i + \beta_4 s_i l_i + \beta_5 s_i^2 + \beta_6 l_i^2 + \varepsilon_i, \qquad i = 1, \ldots, n, \tag{4}$$

where β_1 is a constant. However, it is not always desirable to include all possible predictors in the model. One method to select a set of variables from a set of candidate variables is the step-wise method although there is some criticism surrounding it (see [Wetherill 1986]). We therefore use the "all possible regressions" method which aims to maximise the multiple correlation coefficient (R^2) while maintaining that all regression coefficients have a 95% confidence interval that does not include 0.

Since both the survivability and lethality values are selected by us, we chose to use a grid which covers $S \times L$. The set of survivability scales is defined as

$$S_\Delta = \left\{2\Delta i : i = 0, 1, 2, \ldots, \frac{2}{\Delta}\right\} \subset S, \tag{5}$$

where $\Delta \in (0, 1]$ is a parameter chosen such that $\frac{2}{\Delta}$ is an integer. Likewise, the set of lethality points is defined using the same Δ parameter

$$L_\Delta = \left\{2\Delta i : i = 0, 1, 2, \ldots, \frac{2}{\Delta}\right\} \subset L. \tag{6}$$

The total set of points which we consider is $S_\Delta \times L_\Delta$ which has a total number of $\left(\frac{2}{\Delta} + 1\right)^2$ points. We let $\Delta = 0.25$, giving a total of $9 \times 9 = 81$ points. For each point in $S_\Delta \times L_\Delta$, 200 CAEn replications were run and mean values of each of the MoEs from Table 3 were measured. Due to the central limit theorem, taking the mean results in a close to normal distribution (see [Moore & McCabe 2004] or [Prokhorov 2002]).

6 Results

Using the method outlined in Section 5, two wargames were analysed. Both wargames were against a conventional opposition force in Fallujah. The first, *Case 22A*, used medium weight vehicles (as in Table 1) with a cautious SoM. The second, *Case 41A*, used heavy weight vehicles with an aggressive SoM. Both wargames were run $9 \times 9 = 81$ times, each with 200 repetitions, resulting in a total of 32,400 CAEn replications. Note that all of the models represent surfaces because there are two predominant predictor variables. In all regression model plots, a "•" represents a point that is above and a "∘" represents a point below the fitted surface.

6.1 Case 22A - Medium

The linear regression models for all of the MoEs from Table 3 are presented in Table 4 and the associated plots are in Figure 4.

Table 4: *Regression models for single MoEs in Case 22A - Medium*

MoE		Equation	R^2
$E_{22A}(s,l)$	=	$16.6 + 0.327s - 0.361sl - 0.147s^2 - 0.267l^2$	0.907
$O_{22A}(s,l)$	=	$26.1 + 3.54l + 0.247sl + 0.754s^2 - 0.582l^2$	0.948
$C_{22A}(s,l)$	=	$1.32 + 0.175s + 0.301l - 0.043sl$	0.915
$V_{22A}(s,l)$	=	$1.95 - 0.704s - 0.566l + 0.203sl - 0.12s^2 + 0.0718l^2$	0.975

All of the R^2 values in Table 4 are high. This implies that, for all MoEs, above 90% of the variance can be explained by changes in survivability and lethality. For OPFOR casualties, increasing either survivability, lethality or both has a positive influence on the respective MoE. The same is also true for most of the domain $S \times L$ for EXFOR vehicle casualties. However, increasing lethality or survivability has a negative influence on civilian casualties. Any increase in lethality reduces the number of EXFOR casualties. The direction of change of EXFOR casualties when survivability is changed, depends on both survivability and lethality. To investigate this further, take the gradient of E_{22A}:

$$\nabla E_{22A}(s,l) = \begin{bmatrix} 0.327 - 0.361l - 0.294s \\ -0.361s - 0.534l \end{bmatrix}. \tag{7}$$

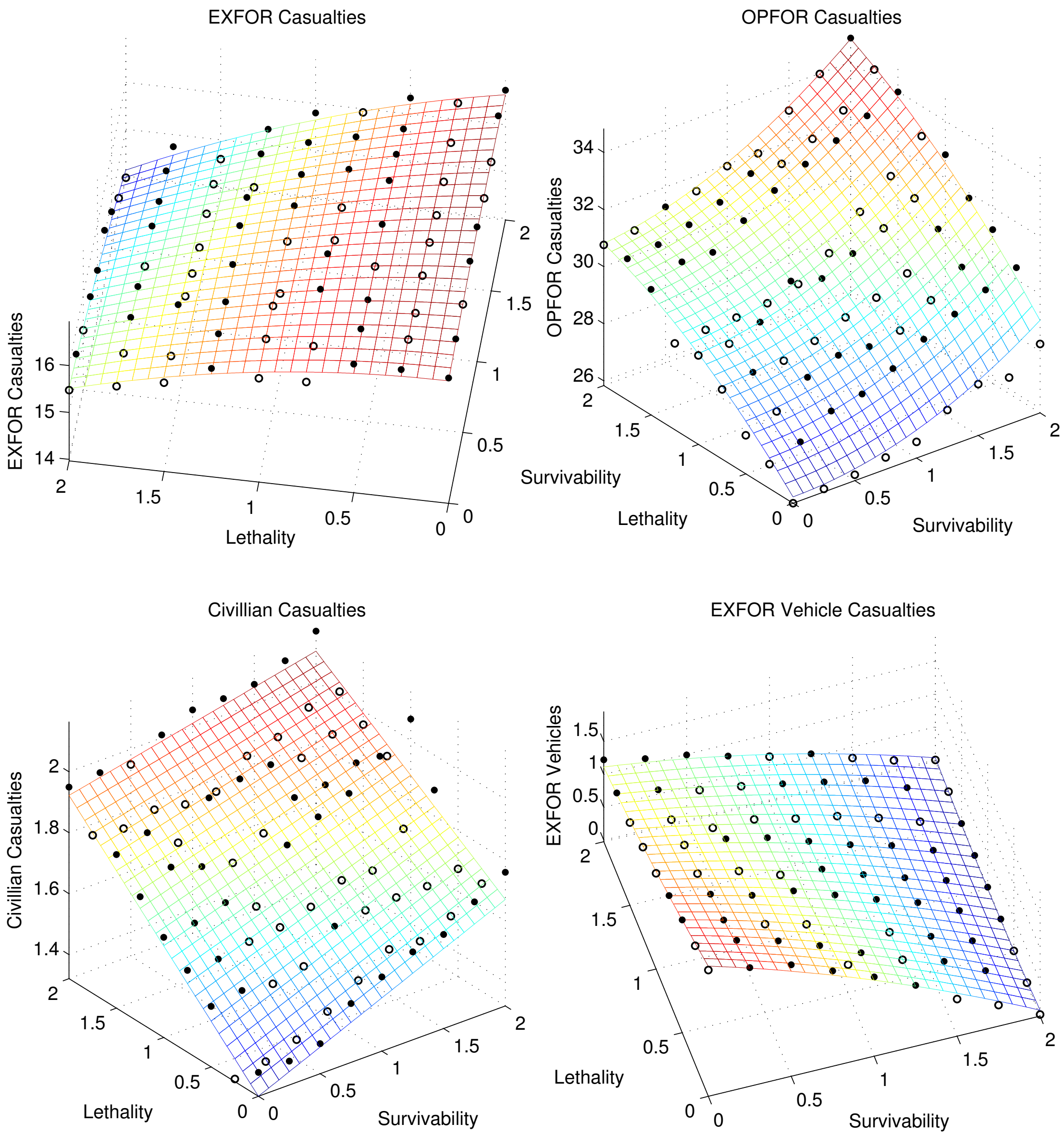

Figure 4: *Individual MoEs for Case 22A - Medium*

The value $\frac{\partial E_{22A}}{\partial s} > 0$ when $s < 1.112 - 1.228l$ and $\frac{\partial E_{22A}}{\partial l} < 0\ \forall(s,l) \in S \times L$. Strangely, this implies that, when starting from a low survivability and lethality mix, small increases in survivability will be detrimental to the number of EXFOR casualties. Conversely, once $s > 1.112 - 1.228l$, EXFOR casualties decrease at a faster rate than the previous increase.

Of interest, the effect of increasing both survivability and lethality has an increasing marginal utility for EXFOR casualties due to the negative sl, s^2 and l^2 coefficients. Generally, in economic terms, marginal utility usually decreases (see [Stigler 1950]). Regarding OPFOR casualties, increasing lethality alone has a decreasing marginal utility whereas increasing survivability has an increasing marginal utility. The EXFOR Vehicle model shows that survivability has more influence than lethality but increasing lethality is still advantageous.

The overall performance linear regression model was calculated for case 22A:

$$p_{22A}(s,l) = 4.36 + 0.0598s + 0.112l + 0.0314s^2, \tag{8}$$

where $p_{22A} : S \times L \to [0, 6]$.

Table 5: *Confidence intervals for Case 22A - Medium*

Variable	**Value**	**95% CI**	
Constant	4.36	[4.3408,	4.3717]
s	0.0598	[0.0294,	0.0902]
l	0.112	[0.1039,	0.1204]
s^2	0.0314	[0.0168,	0.0460]

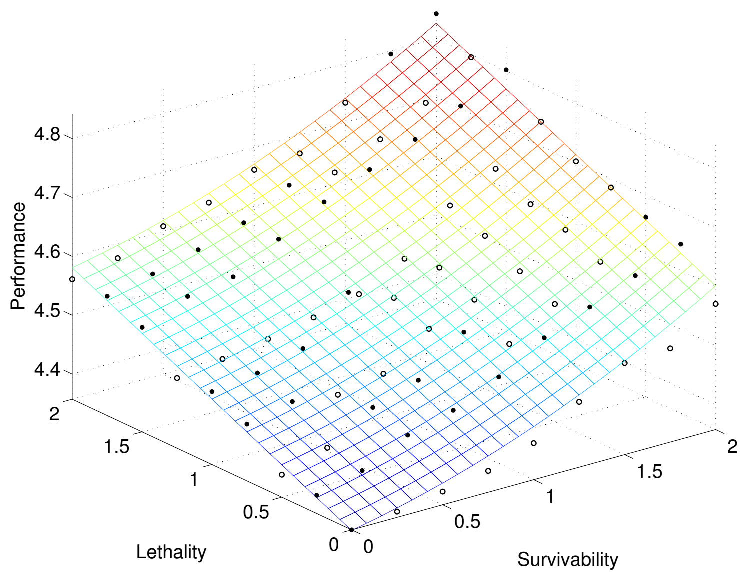

Figure 5: *Performance metric for Case 22A - Medium*

For this model, $R^2 = 0.955$ and the residual errors were verified to be normally distributed using Lilliefor's test ($p \approx 0.5018 \gg 0.05$). Table 5 shows the 95% confidence intervals for the coefficients and Figure 5 shows a plot of Equation (8) with the associated data points.

For this wargame, increasing survivability or lethality improves mission performance. Interestingly, the shape of the function in equation (8) is convex in survivability and linear in lethality. From this model, it is clear that increasing survivability tends to increase mission performance quicker than lethality would, from the initial point $(1, 1)$, given that there is the s^2 term in Equation (8).

6.2 Case 41A - Heavy

The linear regression models for all of the MoEs from Table 3 are presented in Table 6 and the associated plots are in Figure 6.

Table 6: *Regression models for single MoEs in Case 41A - Heavy*

MoE		**Equation**	R^2
$E_{41A}(s,l)$	$=$	$11.4 - 0.153s - 6.11l + 1.55l^2$	0.989
$O_{41A}(s,l)$	$=$	$31.8 + 1.54s + 6.46l - 1.23s^2 - 1.11l^2$	0.989
$C_{41A}(s,l)$	$=$	$2.6 + 3.73l + 0.043s^2 - 0.819l^2$	0.992
$V_{41A}(s,l)$	$=$	$1.4 - 0.586s - 0.211l + 0.122sl - 0.0466s^2 - 0.0389l^2$	0.985

All of the R^2 values from Table 6 are very high. This implies that above 98% of the variance can be explained by changes in survivability and lethality. For EXFOR casualties, increasing either survivability or lethality has a beneficial influence but the effect of lethality is much greater, although diminishing. OPFOR casualties are increased over lethality but there is an optimal amount of survivability at $s_{\max} = \frac{-1.54}{-2\times 1.23} = 0.626$. This indicates that reducing survivability from the baseline of 1 will decrease the number of OPFOR casualties. Note that this finding is heavily influenced by this specific wargame SoM and probably does not generalise. Increasing lethality increases the number of civilian casualties and increasing survivability has a small increasing effect. Clearly, increasing both survivability and lethality improves EXFOR vehicle casualties.

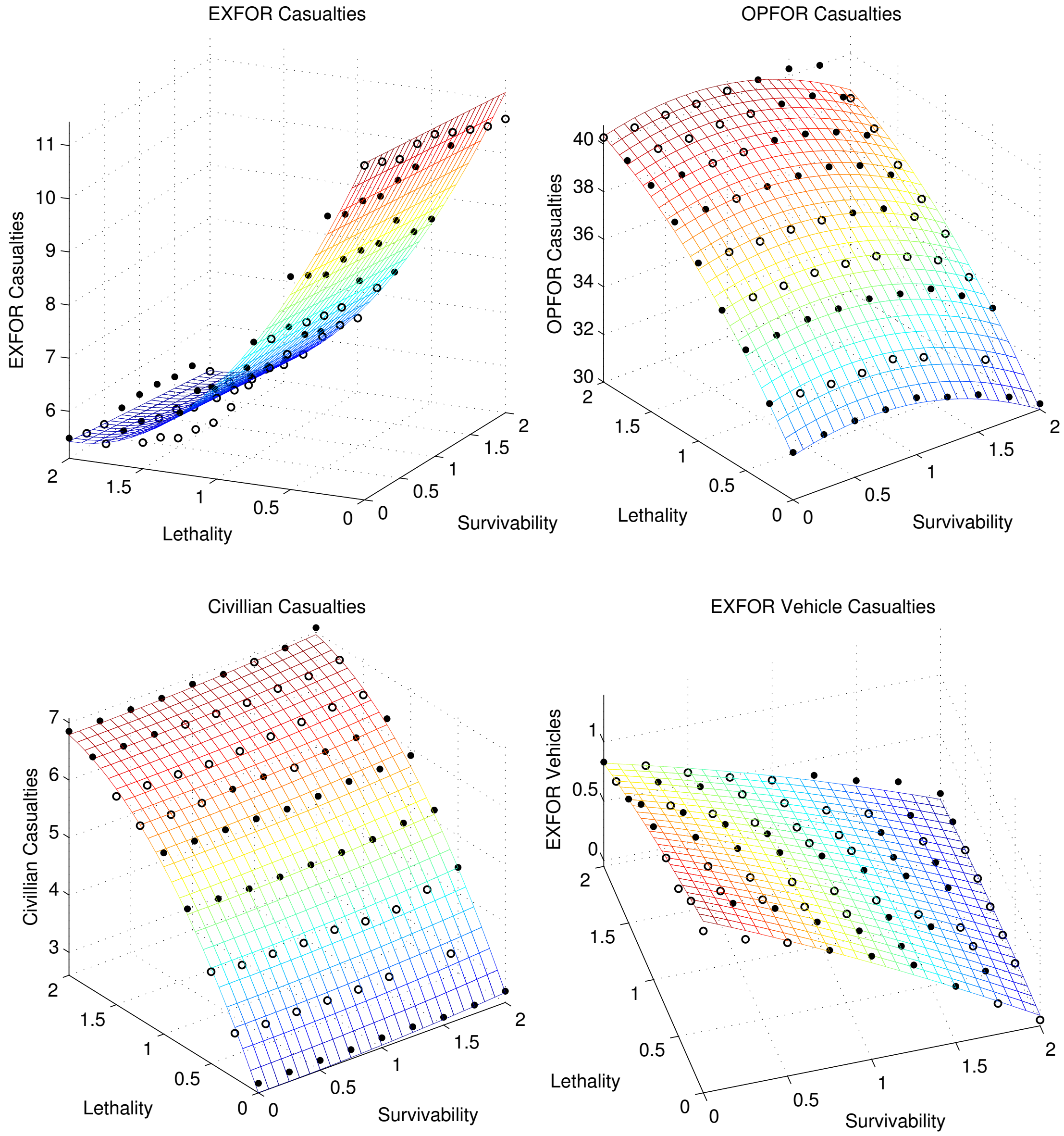

Figure 6: *Individual MoEs for Case 41A - Heavy*

The linear regression model ($R^2 = 0.972$), calculated for case 41A is

$$p_{41A}(s,l) = 4.74 + 0.117s + 0.266l - 0.0187sl - 0.0295s^2 - 0.0533l^2, \quad (9)$$

where $p_{41A}(s,l) : S \times L \to [0,6]$ is the mission performance at the point $(s,l) \in S \times L$. The data points and a plot of the model is shown in Figure 7. The residual errors were verified to not be normally distributed using Lilliefor's test ($p \approx 0.0462 < 0.05$). However, considering the p-value is close to 0.05 and observing Figure 7, the model is a reasonable fit. Table 7 shows the 95% confidence intervals of the coefficients for the regression model in equation (9). For this model, increasing both survivability and lethality increases mission performance. However, as both are increased, the relative increases in performance degrade.

Table 7: *Confidence intervals for case 41A - Heavy*

Variable	Value	95% CI	
Constant	4.74	[4.7235,	4.7544]
s	0.117	[0.0935,	0.1404]
l	0.266	[0.2428,	0.2895]
sl	-0.0187	[-0.0280,	-0.0093]
s^2	-0.0295	[-0.0400,	-0.0189]
l^2	-0.0533	[-0.0637,	-0.0430]

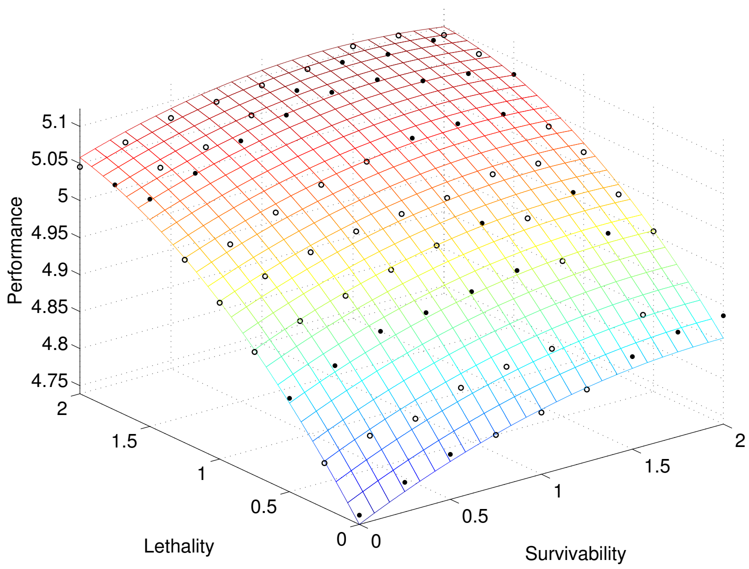

Figure 7: *Performance metric for Case 41A - Heavy*

7 Discussion

Each of the ten regression models can be compared to gain further insights between the two cases that were considered from OF3. Subsection 7.1 compares the individual MoE models between the two cases and Subsection 7.2 compares the overall performance metrics between the two cases.

7.1 Individual Measures of Effectiveness

Regarding EXFOR Casualties, Case 41A performs better than Case 22A in all combinations of survivability and lethality. The main influence for reducing EXFOR casualties in Case 41A is increasing lethality. In contrast, Case 22A is influenced more by increasing both survivability and lethality together.

In both cases, the OPFOR casualty curves show an interesting interaction between lethality and survivability. Case 22A has a positive interaction coefficient resulting in both survivability and lethality together improving performance the most. For Case 41A, there is a local maximum in survivability. Increasing survivability past 0.626 actually reduces the number of OPFOR casualties.

Both Civilian casualty regression models are maximised when lethality and survivability are at their maximum values. Case 22A performs better than Case 41A over all $S_\Delta \times L_\Delta$. In Case 22A, both survivability and lethality increase the number of casualties significantly. In contrast, lethality influences the number of civilian casualties in Case 41A much more than survivability.

Obviously, survivability has a very large influence for EXFOR Vehicle Casualties because when survivability is set to $s = 2$, there must be zero EXFOR vehicle casualties regardless of case. However, in both cases, lethality does influence the number of vehicle casualties.

7.2 Overall Performance

By observing Figures 5 and 7, it is clear that Case 41A has superior performance in the majority of $S \times L$. The range for the data points in $S_\Delta \times L_\Delta$ in Case 22A is $[4.3574, 4.8419]$ and for Case 41A is $[4.7513, 5.1242]$. This is somewhat expected since Case 41A did start with the heavy vehicle option (see Table 1). For this reason, Case 22A has a large opportunity to improve whereas Case 41A is nearer to the maximum possible performance of 6.

Since changes in the SoM and other influences can affect the outcomes of an individual wargame significantly, we are more interested in how the performance changes as survivability and lethality are changed. From the overall performance models, Case 41A (see Subsection 6.2) is analogous to the economic principal of decreasing marginal utility while Case 22A (see Subsection 6.1) has increasing marginal utility. Figure 8 shows the cross section diagonal performance from $[0, 0]$ to $[2, 2]$ with $s = l$ and the associated data points as $\times$s. Note that the fitted curves are plots of equations (8) and (9).

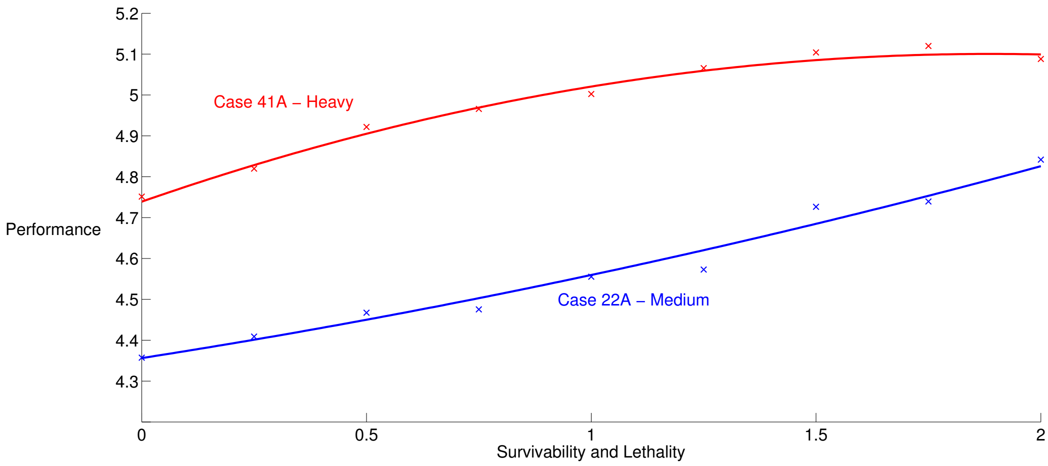

Figure 8: *Performance metrics for both cases on the diagonal*

Taking the gradient of the overall performance model for Case 22A, from Equation (8), yields:

$$\nabla p_{22A}(s,l) = \begin{bmatrix} 0.0598 + 0.0628s \\ 0.112 \end{bmatrix}, \tag{10}$$

and for case 41A,from Equation (9), is:

$$\nabla p_{41A}(s,l) = \begin{bmatrix} 0.117 - 0.0187l - 0.0590s \\ 0.266 - 0.0187s - 0.1066l \end{bmatrix}. \tag{11}$$

At the original point $(s, l) = (1, 1)$, where the wargame was originally played, the values of the gradients in Equations (10) and (11) are:

$$\nabla p_{22A}(1,1) = \begin{bmatrix} 0.12260 \\ 0.112 \end{bmatrix}, \qquad \nabla p_{41A}(1,1) = \begin{bmatrix} 0.0393 \\ 0.14070 \end{bmatrix}. \tag{12}$$

In both cases the values are positive, indicating that any increase in survivability or lethality is beneficial. For Case 22A, increasing survivability is slightly more important than increasing lethality. On the contrary, for Case 41A, increasing lethality results in a quicker improvement in performance compared to increasing survivability. Regarding the interpretation for the results presented, it is likely that the models can be interpolated but caution should be exercised when extrapolating.

The value of $\nabla p_{22A}(s, l)$ is positive in all $S \times L$, indicating that at any point, an increase in survivability or lethality will improve performance. However, for case 41A the gradient is not always positive. For all $S \times L$, the derivative $\frac{\partial p_{41A}}{\partial l} > 0$. However, $\frac{\partial p_{41A}}{\partial s} > 0$ only when $s < 1.983 - 0.317l$. That is, increases in survivability do not always increase performance but increases in lethality do for Case 41A. While this is a striking result (that more survivability could be disadvantageous) seems unintuitive, it may be because the quadratic function does not provide the best fit for the data. Observing the data points in Figure 7, when $s > 1.983 - 0.317l$, the performance seems to plateau.

8 Conclusion

In conclusion, these results suggest that, given a low lethality/survivability vehicle option (as in Case 22A), increasing lethality or survivability a small amount will increase performance. If it is increased further, there will be an even larger improvement in mission performance. In contrast, for the case of a high lethality/survivability (Case 41A) option, a small increase in survivability will improve mission performance slightly and increasing lethality will be much more beneficial. Improving survivability or lethality after the initial improvement will yield less increase in mission performance due to the concave curve.

The findings here can be compared to the qualitative and quantitative findings in OF2 [Finlay et al. 2008] and OF3 [Shine et al. 2009]. Each of the relevant findings is addressed below:

- **Survivability was a key factor in the willingness of EXFOR to commit vehicles to key tasks such as dominating fire lanes and supporting the assault.**
  This finding is not directly addressed by this report. The SoM in Case 41A did use the vehicles in these key tasks as opposed to Case 22A. There is some evidence to suggest that, once a large amount of survivability is obtained, more survivability does not increase performance.

- **Lethality was a key factor in the effectiveness of EXFOR vehicles when employed to perform key tasks.**
  The evidence produced in this report tends to agree with this statement. Case 41A does employ the vehicles in key tasks as opposed to the SoM in Case 22A and lethality improves the performance in Case 41A much more than in Case 22A. A possible generalisation is that for an aggressive SoM, increases in lethality count more and for a cautious SoM, increasing survivability is more desirable.

- **Both environments tended to favour high lethality options with some level of UGV augmentation - with the exception that higher survivability may have compensated for reduced lethality in OF1.**
  Both cases investigated in this report were in a high complexity environment. However, this hypothesis is partly supported by the findings in this report. That is, higher lethality is universally beneficial and in Case 22A, performance would be equal with reduced lethality and increased survivability.

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19. ABSTRACT

We investigate how changes in both survivability and lethality of vehicle options, in a Land 400 setting, affect mission performance. To do this, we construct a quadratic linear regression model with the survivability and lethality as two predictors and various measures of effectiveness as the result. This is done over two separate wargame cases with different vehicle options.